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VACUUM PUMP

This invention relates to a vacuum pump and in particular a compound vacuum pump with multiple ports suitable for differential pumping of multiple chambers.

In a differentially pumped mass spectrometer system a sample and carrier gas are introduced to a mass analyser for analysis. One such example is given in Figure 1. With reference to Figure 1, in such a system there exists a high vacuum chamber 10 immediately following first and second evacuated interface chambers 12, 14. The first interface chamber 12 is the highest-pressure chamber in the evacuated spectrometer system and may contain an orifice or capillary through which ions are drawn from the ion source into the first interface chamber 12. The second, interface chamber 14 may include ion optics for guiding ions from the first interface chamber 12 into the high vacuum chamber 10. In this example, in use, the first interface chamber 12 is at a pressure of around 1 mbar, the second interface chamber 14 is at a pressure of around 10^{-3} mbar, and the high vacuum chamber 10 is at a pressure of around 10^{-5} mbar.

The high vacuum chamber 10 and second interface chamber 14 can be evacuated by means of a compound vacuum pump 16. In this example, the vacuum pump has a first pumping section 18 and a second pumping section 20 each in the form of a set of turbo-molecular stages, and a third pumping section in the form of a Holweck drag mechanism 22; an alternative form of drag mechanism, such as a Siegbahn or Gaede mechanism, could be used instead. Each set of turbo-molecular stages comprises a number (three shown in Figure 1, although any suitable number could be provided) of rotor 19a, 21a and stator 19b, 21b blade pairs of known angled construction. The Holweck mechanism 22 includes a number (two shown in Figure 1 although any suitable number could be provided) of rotating cylinders 23a and corresponding annular stators 23b and helical channels in a manner known per se.

In this example, a first pump inlet 24 is connected to the high vacuum chamber 10, and fluid pumped through the inlet 24 passes through both sets of turbo-molecular stages in sequence and the Holweck mechanism 22 and exits the pump via outlet 30. A second pump inlet 26 is connected to the second interface chamber 14, and fluid pumped through the inlet 26 passes through one set of turbo-molecular stages and the Holweck mechanism 22 and exits the pump via outlet 30. In this example, the first interface chamber 12 may be connected to a backing pump (not shown), which may also pump fluid from the outlet 30 of the compound vacuum pump 16. As fluid entering each pump inlet passes through a respective different number of stages before exiting from the pump, the pump 16 is able to provide the required vacuum levels in the chambers 10, 14.

In order to increase system performance, it is desirable to increase the mass flow rate of the sample and gas. For the pump illustrated in Figure 1, this could be achieved without affecting system pressures by increasing the capacity of the compound vacuum pump 16 by increasing the diameter of the rotors 21a and stators 21b of the turbo-molecular stages of the second pumping section 20. For example, in order to double the capacity of the pump 16, the area of the rotors 21a and stators 21b would be required to double in size. In addition to increasing the overall size of the pump 16, and thus the overall size of the mass spectrometer system, the pump 16 would become more difficult to drive in view of the increased mass acting on the drive shaft 32 due to the larger rotors and stators of the second pumping section 20. Alternatively, if the system flow rate is increased and the pump is not increased in capacity, the pressure at the inlet to the turbomolecular stages, 20, may exceed operational limits. It is a known consequence of this type of turbomolecular technology that operation above approximately 10^{-3} mbar may cause excessive heat generation and severe performance loss and may even be detrimental to the pump reliability.

It is an aim of at least the preferred embodiments of the present invention to provide a differential pumping, multi port, compound vacuum pump, which can

enable the mass flow rate in an evacuated system to be increased specifically where required without significantly increasing the size of the pump.

In a first aspect, the present invention provides a vacuum pump comprising a first pumping section, a second pumping section downstream from the first pumping section, a third pumping section downstream from the second pumping section, a first pump inlet through which fluid can enter the pump and pass through each of the pumping sections towards a pump outlet, and a second pump inlet through which fluid can enter the pump and pass through only the second and the third pumping sections towards the outlet, wherein the third pumping section comprises a helical groove formed in a stator thereof, and at least one of the first and second pumping sections comprises a helical groove formed in a rotor thereof.

Thus, the second, turbo-molecular pumping section 20, for example, of the known pump described with reference to Figure 1 can be effectively replaced by a pumping section having an externally threaded, or helical, rotor. In such an arrangement, the inlet of the helix will behave in use like a rotor of a turbo-molecular stage, and thus provide a pumping action through both axial and radial interactions. In comparison, a Holweck mechanism with a static thread, such as that indicated at 22 in Figure 1, pumps fluid by nominally radial interactions between the thread and cylinder. Beyond a certain radial depth of thread, this mechanism becomes less efficient due to the reducing number of radial interactions, and it is for this reason that the typical capacity of a "static" Holweck mechanism is limited to less than that of an equivalent diameter turbo-molecular stage, which pumps by nominally axial interactions and has greater radial blade depths. By providing an externally threaded rotor, the inlet of the thread of the externally threaded rotor can be made much deeper radially than the helical groove in a static Holweck mechanism, resulting in a significantly higher pumping capacity. By appropriate design, the capacity of an externally threaded, deep grooved helical rotor can be comparable to that of an equivalent diameter turbomolecular stage when operating at low inlet pressures, for example below 10^{-3} mbar. The advantage of the use of such a deep groove helical rotor in place

of a turbomolecular stage is that it can offer a higher capacity at higher inlet pressures (above 10^{-3} mbar) with lower levels of power consumption / heat generation – a limiting factor of the operational window of turbomolecular pumps. By utilising a deep groove helical rotor and raising the inlet pressure above that which would be ideal for a turbomolecular pump, more flow can be pumped without requiring an increase in effective pumping capacity, thus meeting the requirements of increased evacuated system performance without increasing the size of the pump envelope.

Minimising the increase in pump size/length whilst increasing the system performance where required can make the pump particularly suitable for use as a compound pump for use in differentially pumping multiple chambers of a bench-top mass spectrometer system requiring a greater mass flow rate at, for example, the middle chamber to increase the sample flow rate into the analyser with a minimal or no increase in pump size.

Furthermore, offering static surfaces adjacent to the outlet of the helical rotor stage, by providing a third pumping section having a helical groove formed in a stator thereof, can further optimise pump performance.

As the molecules transfer from the inlet side of the rotor towards the outlet side, the pumping action is similar to that of a static Holweck mechanism, and is due to radial interactions between rotating and stationary elements. Therefore, the helical rotor preferably has a tapering thread depth from inlet to outlet (preferably deeper at the inlet side than at the outlet side). Furthermore, the helical rotor preferably has a different helix angle at the inlet side than at the outlet side; both the thread depth and helix angle are preferably reduced smoothly along the axial length of the pumping section from the inlet side towards the outlet side.

In a preferred arrangement, the first pumping section comprises at least one turbo-molecular stage, preferably at least three turbo-molecular stages. The first and

second pumping sections may be of a different size/diameter. This can offer selective pumping performance.

Thus, preferably the helical rotor is located downstream from said at least one turbo-molecular stage. To ensure that fluid enters the helical rotor with maximum relative velocity to the helix blades, and thereby optimise pumping performance, the turbo-molecular stage is preferably arranged such that the molecules of fluid entering the helical rotor have been emitted from the surface of a stator of the turbomolecular stage by placing a stator stage as the final stage of the turbomolecular section adjacent the inlet side of the helical rotor.

In addition to the helical rotor, the second pumping section may further comprise at least one turbomolecular pumping stage downstream from the helical rotor. By positioning the second inlet such that it extends partially about the helical rotor, as opposed to being axially spaced therefrom, the capture rate of molecules from the chamber connected to the second inlet can be improved, in particular for relatively light gases, thereby reducing the pressure in the chamber evacuated through the second inlet. Therefore, in a second aspect the present invention provides a vacuum pump comprising a first pumping section and, downstream therefrom, a second pumping section, a first pump inlet through which fluid can enter the pump and pass through both the first pumping section and the second pumping section towards a pump outlet, and a second pump inlet through which fluid can enter the pump and pass through, of said sections, only the second pumping section towards the outlet, wherein one of the first and second pumping sections comprises an externally threaded rotor and one of the first and second pump inlets extends at least partially about the externally threaded rotor.

The invention also provides a differentially pumped vacuum system comprising two chambers and a pump as aforementioned for evacuating each of the chambers. One of the pumping sections arranged to pump fluid from a chamber in which a pressure above 10^{-3} mbar, more preferably above $5x10^{-3}$ mbar, is to be generated preferably comprises an externally threaded rotor.

Preferred features of the present invention will now be described, by way of example only, with reference to the accompanying drawings, in which:

Figure 1 is a simplified cross-section through a known multi port vacuum pump suitable for evacuating a differentially pumped, mass spectrometer system;

Figure 2 is a simplified cross-section through a first embodiment of a multi port vacuum pump suitable for evacuating the differentially pumped mass spectrometer system of Figure 1;

Figure 3 illustrates an externally threaded rotor of the pump of Figure 2;

Figure 4(a) is a simplified cross-section through a second embodiment of a multi port vacuum pump suitable for evacuating the differentially pumped mass spectrometer system of Figure 1;

Figure 4(b) is a plan view of the pump of Figure 4(a);

Figure 5 illustrates the configuration of a pump inlet of the pump of Figure 4(a);

Figure 6(a) is a simplified cross-section through a third embodiment of a multi port vacuum pump suitable for evacuating the differentially pumped mass spectrometer system of Figure 1; and

Figure 6(b) is a plan view of the pump of Figure 6(a).

With reference to Figure 2, a first embodiment of a vacuum pump 100 suitable for evacuating at the least the high vacuum chamber 10 and intermediate chamber 14 of the differentially pumped mass spectrometer system described above with reference to Figure 1 comprises a multi-component body 102 within which is mounted a shaft 104. Rotation of the shaft is effected by a motor (not shown), for

example, a brushless dc motor, positioned about the shaft 104. The shaft 104 is mounted on opposite bearings (not shown). For example, the drive shaft 104 may be supported by a hybrid permanent magnet bearing and oil lubricated bearing system.

The pump includes three pumping sections 106, 108 and 112. The first pumping section 106 comprises a set of turbo-molecular stages. In the embodiment shown in Figure 2, the set of turbo-molecular stages 106 comprises three rotor blades and three stator blades of known angled construction. A rotor blade is indicated at 107a and a stator blade is indicated at 107b. In this example, the rotor blades 107a are mounted on the drive shaft 104.

The second pumping section 108 comprises an externally threaded rotor 109, as shown in more detail in Figure 3. The rotor 109 comprises a bore 110 through which passes the drive shaft 104, and an external thread 111a defining a helical groove 111b. The depth of the thread 111a, and thus the depth of the groove 111b, can be designed to taper from the inlet side 111c of the rotor 109 towards the outlet side 111d. In this embodiment, the thread 111a is deeper at the inlet side than at the outlet side, although this is not essential. The helix angle, namely the angle of inclination of the thread to a plane perpendicular to the axis of the shaft 104, of the rotor can also vary from the inlet side to the outlet side; in this embodiment, the helix angle is shallower at the outlet side than at the inlet side, although again this is not essential.

As shown in Figure 2, downstream of the first and second pumping sections is a third pumping section 112 in the form of a Holweck or other type of drag mechanism. In this embodiment, the Holweck mechanism comprises two rotating cylinders 113a, 113b and corresponding annular stators 114a, 114b having helical channels formed therein in a manner known per se. The rotating cylinders 113a, 113b are preferably formed from a carbon fibre material, and are mounted on a disc 115, which is located on the drive shaft 104. In this example, the disc 115 is

also mounted on the drive shaft 104. Downstream of the Holweck mechanism 112 is a pump outlet 116.

As an alternative to individually mounting the rotary elements 107a, 109 and 115 on the drive shaft 104, one or more these elements may be located on, preferably integral with, a common impeller mounted on the drive shaft 104, with the carbon fibre rotating cylinders 113a, 113b of the Holweck mechanism 112 being mounted on the rotating disc 115 following machining of these integral rotary elements.

As illustrated in Figure 2, the pump 100 has two inlets; although only two inlets are used in this embodiment, the pump may have three or more inlets, which can be selectively opened and closed and can, for example, make the use of internal baffles to guide different flow streams to particular portions of a mechanism. The first, low fluid pressure inlet 120 is located upstream of all of the pumping sections. The second, high fluid pressure inlet 122 is located interstage the first pumping section 106 and the second pumping section 108.

In use, each inlet is connected to a respective chamber of the differentially pumped mass spectrometer system. Fluid passing through the first inlet 120 from the low pressure chamber 10 passes through each of the pumping sections 106, 108, 112 and exits the pump 100 via pump outlet 116. To ensure that fluid enters the helical rotor 109 of the second pumping stage 108 with maximum relative velocity to the helix blades (threads), and thereby optimise pumping performance, in this embodiment the first pumping section 106 is preferably arranged such that the molecules of fluid entering the helical rotor 109 have been emitted from the surface of the final stator 107c of that section 106, and the subsequent stage of the Holweck mechanism 112 is also preferably stationary to offer static surfaces at the outlet side 111d of the rotor 109.

Fluid passing through the second inlet 122 from the middle pressure chamber 14 enters the pump 100 and passes through pumping sections 108, 112 only and exits the pump via outlet 116. Fluid passing through a third inlet 124 from the

high pressure chamber 12 may be pumped by a backing pump (not shown) which also backs the pump 100 via outlet 116.

In this embodiment, in use, the first interface chamber 12 is at a pressure of around 1 mbar, the second interface chamber 14 is at a pressure of around 10^{-2}-10^{-3} mbar, and the high vacuum chamber 10 is at a pressure of around 10^{-5} mbar. Thus, in comparison to the example illustrated in figure 1, the pressure in the second interface chamber 14 can be increased in the embodiment shown in Figure 2. By increasing the pressure from around 10^{-3} mbar to around 10^{-2} mbar, the requirements on pumping speed are reduced by the ratio of the old to the new pressure for a fixed flow. Therefore, for example, if the pressure is raised ten-fold, and the flow rate is doubled, the pumping speed at this new pressure can be reduced 5-fold, although in use it would clearly be beneficial to maintain as high a pumping speed as possible to maximise the flow rate from the second interface chamber 14. A turbo-molecular pumping section such as that indicated at 20 in Figure 1 would not be as effective as the pumping section 108 in Figure 2 at maintaining a pressure of around 10^{-2} mbar in the second interface chamber 14, and would in use consume more power, generating more heat than pumping section 108 and potentially have less performance due to operating further outside its effective performance range.

Thus, a particular advantage of the embodiment described above is that the mass flow rate of fluid entering the pump from the middle chamber 14 can be at least doubled in comparison to the known arrangement shown in Figure 1 without any increase in the size of the pump. In view of this, the flow rate of the sample entering the high vacuum chamber 10 from the middle chamber can also be increased, increasing the performance of the differentially pumped mass spectrometer system.

Figures 4(a) and 4(b) illustrate a second embodiment of a vacuum pump 200 suitable for evacuating at the least the high vacuum chamber 10 and intermediate chamber 14 of the differentially pumped mass spectrometer system described

above with reference to Figure 1. The second embodiment is similar to the first embodiment, with the exception that the second pumping section 108 has been extended towards the first pumping section 106. This may be achieved by simply increasing the length of the second pumping section, as shown in Figure 4(a) where the increase in length is indicated at 209, or by displacing the rotor 109 towards the first pumping section 106 As a result, rather than both of the first and second pumping sections 106, 108 being axially displaced relative to the first and second inlets 120, 122, as in the first embodiment, part of the second pumping section 108 is now axially adjacent the second inlet, such that the second inlet 122 now extends partially around the second pumping section 108. Figure 5 illustrates schematically how at least the second inlet 122 extends partially around the cylindrical inner wall 202 of the body 102 of the pump 200. By circumferentially exposing part of the helical rotor 109 to the middle chamber 14 via the second inlet port 122, the capture rate of molecules from the chamber 14 can be improved in comparison to the first embodiment, thereby further lowering the pressure in the middle chamber 14 and further increasing the performance of the differentially pumped mass spectrometer system.

Figures 6(a) and 6(b) illustrate a third embodiment of a vacuum pump 300 suitable for evacuating at the least the high vacuum chamber 10 and intermediate chamber 14 of the differentially pumped mass spectrometer system described above with reference to Figure 1. This third embodiment is similar to the prior art pump 16 shown in Figure 1, with the exception that the second pumping section 20 now includes a helical rotor 302 located between the turbomolecular stages of the second pumping section 20 and the first pumping section 18. As in the second embodiment described above, part of the second pumping section 20 is now axially adjacent the second inlet 26, such that the second inlet 26 now extends partially around a helical rotor 302 of the second pumping section 20. Due to the circumferential exposure of part of the helical rotor 302 of the second pumping section 18 to the middle chamber 14, the capture rate of molecules from the middle chamber 14 can be increased in comparison to the prior art, thereby

lowering the pressure in the middle chamber 14 and increasing the performance of the differentially pumped mass spectrometer system.